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ScienceDirect

Procedia Engineering 120 (2015) 302 – 305

Procedia Engineering

www.elsevier.com/locate/procedia

EUROSENSORS 2015

Modelling of time reversal for localized tactile feedback on displays

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Abstract

A study on local haptic feedback on panels by using a limited number of acoustic transducers is presented. Feasibility is discussed to enhance the time reversal (TR) technique [1] towards a virtual model-based calibration instead of an empirical. Reversibility of a structural elastic wave is used to refocus on arbitrary focal points. This enables producing a localized haptic interaction to a fingertip. The contribution includes the theoretical background, a simulation study and its empirical validation.

Peer-review under responsibility of the organizing committee of EUROSENSORS 2015

Keywords: haptic interaction, acoustic time reversal, structure borne sound, numerical calibration

1. Motivation

Operating a touch-screen is a matter of course in our everyday life. However, it is not taken for granted for everyone (e.g. in case of individual physical constraints) or in everyday situation (e.g. unfavorable external conditions). Then, the usability is limited due to an absent haptic feedback as in case of real keys or buttons. A prospective user-oriented support addresses the local mechanical interaction with the finger. For this haptic feedback the local interference of acoustic waves in terms of a mechanical vibro-tactile sensation (impulse, vibration) at several positions on the screen can be applied. Thereby, visually accessible elements can be supported by haptic feedback. The technique behind it bases on the acoustic time reversal. Time Reversal (TR) in acoustics is subject of different international research activities, starting with the work of Fink et al. [1], [2]. The approach takes advantage of the reversibility of the forward and backward propagation of acoustic waves between fixed transceiver points. In contrast to known empirical calibration procedures this contribution uses simulations to

- set up a database to selectively address several points of feedback on the panel
- define the actuators signals with respect to the contrast and resolution of tactile sensation in a focal point,
- the potential to selectively focus on multiple points at the same time and through an intermediate layer and
- reduce the excitation length of the time reversed signal covering the main wave paths only.

Another objective is to influence the signal content. This concerns wave mode selectivity with spatial filter elements and the duration of the actuator signals as well as the consistency of simulated and experimental results with respect on the focal quality. For the sake of briefness those results will be presented at the conference only.

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doi:10.1016/j.proeng.2015.08.621

2. Basic physic conditions for haptic feedback

The haptic feedback that can be felt by a human fingertip (haptic perceptual detection threshold) depends on the vertical and horizontal displacement of the surface (acoustic energy), the excitation frequency (wavelength) and the shape of the transient displacement. The lateral spatial resolution of the perceptual active area mainly depends on the wavelength. The maximum of the haptic sensitivity can be found at a vibration frequency of $f = 200 \ldots 300$ Hz. The corresponding sensitivity levels (perceptual threshold) of the elongation at these frequencies are in the range of $\Delta x >$ 0.2 µm for transversal displacement and $\Delta z > 5$ µm for displacements vertical to the skin surface. A cumulative movement of the finger over the surface additionally lowers the threshold. Due to the ratio of the propagation velocity (larger wavelength) to the dimension of the focus point the shear mode is unsuitable despite the higher sensitivity (0.2 µm). Accordingly the presented work concentrates on the basic asymmetric mode A0.

Typically common touch sensitive displays are made of glass or plastic material with a thickness in the range of 2 mm to 5 mm [3]. Because of the larger physical wavelength on such plates neither local steplike thresholds nor multiple arbitrary focus points in size and spacing of a human fingertip can be realized at the haptic frequencies (<300 Hz). Thus, the selective generation of larger feedback spots on comparatively large plate structures seems to be realistic for now. Signals with higher frequencies will need a higher excitation power due to the lower surface displacement. Furthermore, additional acoustic perceptible disturbing signals would occur, which normally are not wanted. Nevertheless, the study addresses higher frequency signals (< 10 kHz) also (Fig. 1) combined with a haptic frequency modulation. This improves the spatial resolution by remaining the perceptual feedback. Transient 3D-simulation including the structural acoustic equations supports investigations. Both the phase velocities as a function of frequency (Fig. 1) and the transient displacement (Fig. 2) can be derived with the model.

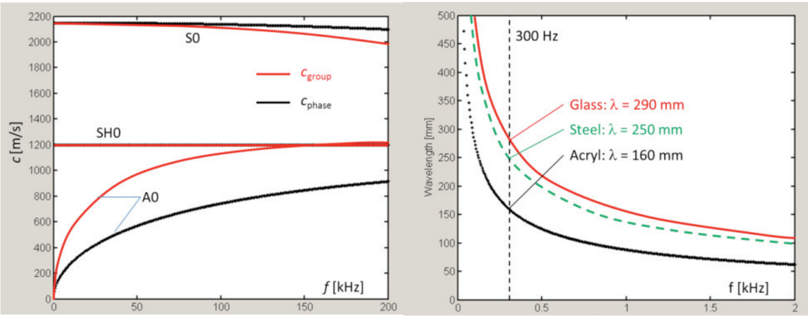
3. Time reversal technique (non-iterative)

The reversibility of an elastic wave can be used to refocus a signal on a point by time reversal (TR) techniques. Numerous application fields are connected to this technology, such as medical intervention, non-destructive testing or impact localization on touchscreen systems. Here a lot of simple localization approaches exists using the acoustic interaction of a finger impact [2]. However, the reverse process producing a perceptual local haptic feedback with elastic waves is not sufficiently supported up to now [3]. Here, TR can provide a user-oriented support by realizing vibro-tactile sensations at virtual buttons or other control elements on the screen. Main challenges or necessary improvements are the realization of a tempo-spatial localized short pulse on the surface with elongations in the range of the perceptual threshold and the reduction of distributed signal clutter (on the rest of the surface).

The ideal replication of the original impulse by time reversal of the divergent wave field requires a time reversal mirror, whose unlimited number of excitation points forms a curve integral surrounding the original excitation point and gathering the total transient acoustic field crossing that curve. Alternatively, an unlimited number of multiple reflections (without damping) is needed to approximate the same divergent wave field by virtual sources at the reflecting boundaries. Because of damping only a limited number of excitation points will be applicable. Hence, their number and positions need to be optimized to approximate the original signal. Therefore the contribution addresses the local haptic feedback on panels by using a limited number of acoustic transducers with regular and randomized patterns. Normally the time reversal is done by measuring the impulse response or the spectral transfer function between two separated single transceivers. In our case we try to establish a fully automated virtual calibration by finite element modelling.

4. Dispersion-Model of an ideal plate

In theory there are an unlimited number of different guided modes of structural elastic waves that can propagate on plate structures. The phase and group velocities of each mode are dispersive and a function of frequency. Hence, it is necessary to evaluate each mode concerning its cut-off frequency, wavelength and the vertical displacement, which is supposed to be the main parameter for haptic interaction. For solving the differential equations that describe the elastic transient behavior depending on the geometry (plate thickness), the elasticity and the Poisson's number a numeric two dimensional model is used. The model consists of a plate slice assuming Floquet periodicity of the displacement vector. The solution of the phase velocities as a function of frequency based on the finite elements simulation enables the geometric design of the plate and the selection of single wave modes towards an optimized haptic feedback. Normally the solution is depicted within a dispersion diagram. As an example Fig. 1 a represents the dispersive characteristics of the velocities for an acrylic material and Fig. 1 b depicts the wavelengths for two typical materials used for displays in comparison to a steel plate. Table 1 summarizes the corresponding acoustic parameters. In the range of the haptic frequency (300 Hz) the wavelength varies from 160 mm to 290 mm for the asymmetric mode A0. The next higher Rayleigh-mode SH0 has a quite larger wavelength, which is not suitable for high spatial resolution in focal points.



Tab. 1: Material parameters

Material	Acryl	Glass	Steel
ρ [kg/m³]	1200	1590	7850
$c_{Long.}$ [m/s]	2700	6790	5778
$c_{Trans.}$ [m/s]	1200	4321	3194
E [GPa]	4,76	68.9	205
μ	0,38	0.16	0,28

Fig. 1. (a) Dispersion diagram for phase and group velocities of asymmetric (A0), symmetric (S0) lamb modes and Rayleigh mode (SH0) on an acrylic plate with thickness of d = 2 mm. (b) Figure 3: Wavelength of asymmetric lamb-mode A0 for plates with thickness of d = 2 mm and different materials (refer to Tab.1).

5. Calibration-Model with finite elements simulation

A three dimensional model for plates was created to solve for the stationary eigenmodes and the transient behavior of short time pulses that are excited from different multiple transducer locations. Especially the reflection and mode conversion at the boundaries needs to be modelled because it is essential for the time reversal process with a reduced number of excitation points. The parameter studies covered variations of the number and placement of the source points, the plates' material and thickness, the frequency and fixed and floating bearing of the boundaries. Here the material parameters don't need to be exact since the time reversed signal is reduced to the main propagation path (truncated to 30% of the time window with high signal to noise ratio) and normalized. The 1-bit-quantization [4] is not applied. In this contribution the influence of source patterns is discussed only, since the main goal of the simulation is to provide a virtual description of the necessary input data at the transducers in order to excite a time reversed signal at a desired focus location. The 3D-solution of the transient divergent wave fields generated by different excitation (and later focus) points (Fig. 2a) helps to determine the needed positions and number of source points for time reversal. As an example the simulation results for different plastic and glass plates are illustrated. Fig. 2a depicts the forward-propagation of an elastic impulse at the desired focal point in case of a glass plate with dimensions of [500x500x2] mm.

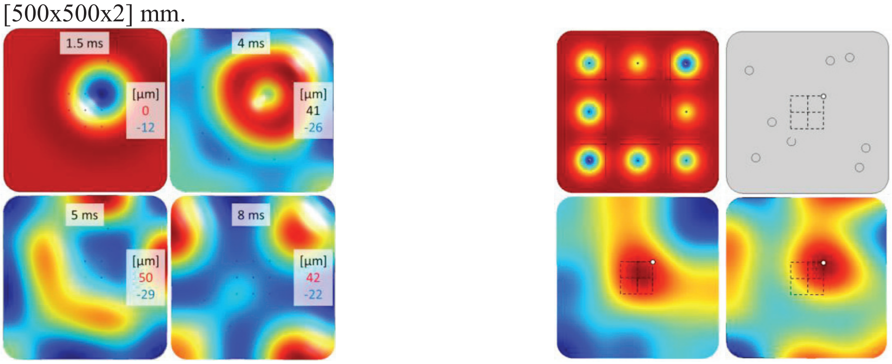


Fig. 2. Simulation of Glass-plate (500 x 500 x 2) mm: (a) Forward-Propagation (vertical displacement) of a gauss pulse (asymmetric lamb-*mode* A0 c_{A0} = 87 m/s, λ = 290 mm) for different time steps. (b) Time reversal with 8 transducers (excitation points) with regular (b left) and

randomized (b right) pattern focusing on the same focal point (white spot) with a spatial offset to the plates center of $\Delta x = \Delta y = +50$ mm (wavelength at 325 Hz: $\lambda_{A0} = 290$ mm): top: excitation timestep, down: focus timestep (time reversal)

Based on the wave field snapshots of two chosen examples (Fig. 2b) it can be seen that a regular pattern with a large number of transducers would give best results for focusing in the plate center (Fig. 2b left). In contrast a shifted, off-center focus requires an irregular pattern. In Fig. 2a the time steps t = 1.5 ms and t = 8 ms represent the ideal focal time for haptic feedback and the ideal source pattern for a time reversal.
A symmetric placement of the transducer will force a symmetric wave pattern on the plate which could mask a focus displacement. Hence, to avoid predominant wave patterns, a randomized transducer placement is necessary. Fig. 2b illustrates the focus quality by time reversal for a regular symmetric transducer pattern and a randomized (not optimized) pattern with 8 source points. In the left figure the interference with the predominant symmetric wave pattern lead to an insufficient replication of the focal point (white circle). In contrast the irregular transducer arrangement (right figure) supports the formation of a shifted focal point.

6. Results and verification

The current studies illustrate that an arbitrary time and spatial focusing of an elastic impulse can be established in the perceptual haptic frequency range. With an irregular transducer pattern (Fig. 3), the forward simulation of haptic impulse are adequate to virtually calibrate a data set for time reversal haptic feedback on arbitrary focal points (Fig. 3). The size of the focus is determined by the physical wavelength of approx. 10 cm on plastic or glass plates with a thickness of 2 mm. Additionally, the haptic quality of the focal signal could be improved by switching the frequency to an eigenmode of the plate.
Supplementary to the numerical studies a measurement system was established which enables the time reversal investigation on plates with 16 independent channels. The elongation of the plate at arbitrary points is captured with a laser triangulation sensor. During the empirical studies a variety of electrodynamic and acoustic transducers (piezoceramic, vibration motor, structure-borne loudspeaker, voice coil motor) were tested towards their ability to excite an elastic A0 wave on different plates in the haptic frequency range (200…300) Hz. For the sake of briefness these results and the empirical verification will be discussed at the conference.

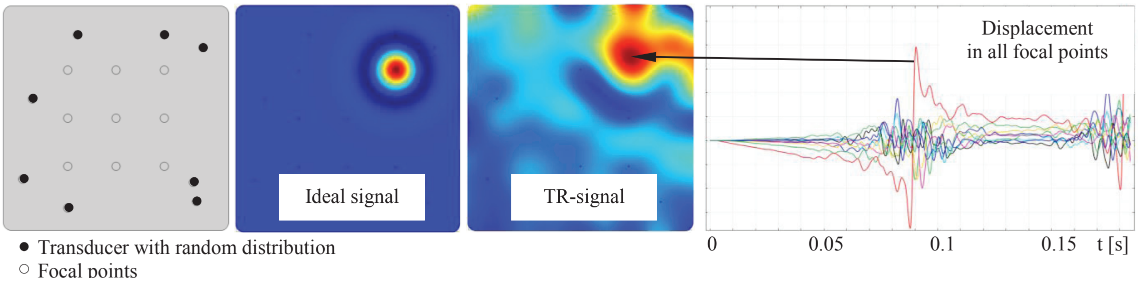


Fig. 3. (a) Simulation model of a plastic plate [700 x 700 x 2]mm with 8 randomly distributed transducers and 9 selected focal points; (b) 2D-distribution of ideal localized displacement and (c) real displacement in focal point and (d) comparison of the displacements of all focal points.

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